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Observations of binaries in AGB, post-AGB stars and Planetary Nebulae

Eric Lagadec¹, Olivier Chesneau¹

¹*Laboratoire Lagrange, UMR7293, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, 06304 Nice Cedex 4, France*

Abstract. During the last years, many observational studies have revealed that binaries play an active role in the shaping of non spherical planetary nebulae. We review the different works that lead to the direct or indirect evidence for the presence of binary companions during the Asymptotic Giant Branch, proto-Planetary Nebula and Planetary Nebula phases. We also discuss how these binaries can influence the stellar evolution and possible future directions in the field.

1. Introduction

While most of the low and intermediate mass stars (between ~ 0.8 and $\sim 8 M_{\odot}$) appear more or less spherical on the main sequence or on the Red Giant branches, Planetary Nebulae (PNe) can harbour a wide variety of shapes and be elliptical, bipolar or multipolar. During the last years, more and more evidences have been gathered that this departure from spherical was linked to the influence of a binary companion. In these paper, we will review the different works that lead to the discovery of direct and indirect evidences for binary companion in the heart of planetary nebulae, post-AGBs and AGB stars and discuss possibilities to detect more binaries in AGB stars.

2. Equatorial overdensities and jets

The shaping of planetary nebulae has been the subject of studies for decades now. As early as in the late 1970s, Kwok et al. (1978) proposed that the thin shells of planetary nebulae were due to the interaction of a fast stellar wind (the PN wind) with the slower, denser material ejected during the AGB phase. This Interacting Stellar Wind Model (ISW) was very efficient at explaining the observed morphology and density of PNe shells. During the next decade, observation of PNe revealed that collimated outflows were common in PNe (Balick et al., 1987). It was suggested that equatorial overdensities could lead to the formation of such outflows. Many models have since been proposed to explain the formation of the central overdensities and bipolar jets, including the presence of a binary companion (via e.g. common envelope evolution or Roche-lobe overflow) or magnetic fields. A very interesting review on this topic was written by Balick and Frank (2002). High angular resolution and high contrast observations of PNe with the *Hubble Space Telescope* (HST) revealed a vast variety of shapes and provided us images widely used for outreach. These images also confirmed that

aspherical PNe were common and that spherical PNe were more the exception than the rule. Dark lanes observed in the optical images were clear indirect proofs of the presence of equatorial dusty structures (see e.g. Matsuura et al., 2005). Unfortunately, observations in the optical enable us to study those equatorial structures via scattered light only. Observations at longer wavelengths are needed to directly characterise the equatorial overdensities needed to explain the formation of bipolar PNe. This was made possible with the advance of high angular resolution techniques in the infrared (e.g. adaptive optics and interferometry) and the millimetre (imaging and interferometry). Infrared observations, using interferometry (e.g., Chesneau et al., 2006, 2007, Lykou et al., 2011) or direct imaging with adaptive optics (e.g. Lagadec et al., 2006), resolved these equatorial structures. It was also achieved in the millimetre domain with CO observations (e.g. Peretto et al., 2007, Alcolea et al., 2007). The infrared observations are sensitive to dust emission and help us study the dust spatial distribution and content. The millimetre observations enable us to study the CO gas spatial distribution and dynamics, thanks to their spectral resolution. Two kinds of equatorial overdensities have thus been observed: torii and stratified discs.

Torii are massive (masses of the order of \sim a solar mass or more), have a low expansion velocity (typically a few km/s, see e.g. Peretto et al. (2007)). Their kinematic is dominantly radial and their angular momentum is limited. They are short-lived, so that if the mass loss stops, the material will rapidly expand and vanish.

Discs exhibit clear vertical stratifications, with scale height governed by the gas pressure only. They have very small aperture angle (less than ~ 10 degrees typically) and their kinematic is Keplerian, with a small expansion component (< 10 km/s) (see e.g. Bujarrabal et al., 2013, Deroo et al., 2007). Their lifetimes are much larger than the torii described above and are comparable or larger than the typical lifetime of a PN, which is typically few tens of thousand years (van Winckel 2003).

High angular observations, mostly with the HST, also revealed the presence of multipolar PNe. The formation of such nebulae can not be explained with an isotropic wind interacting with an equatorial density. Sahai & Trauger (1998) proposed that this could be due to precessing jets. The presence of jets was confirmed by a study of proto-PNe by Bujarrabal et al. (2001). They used CO observations to measure the mass, linear momentum and kinetic energy of bipolar flows in proto-PNe. They found that in about 80% of the PPNe, the momentum of the outflow is too high to be powered by radiation pressure only (up to ~ 1000 times larger). An extra source of angular momentum is thus needed to explain the presence of these jets.

3. Binaries as shaping agents

So far, we have shown that equatorial overdensities and jets are shaping most of the PNe. The question that need to be answered now is how are these discs/torii and jets formed. Different models have been proposed to explain the formation of jets, involving either the magnetic field (e.g. Garcia-Segura et al., 2005) or the influence of a binary companion (stellar or substellar) as the main shaping agent (e.g. Soker et al., 2004). Two key works certainly settled the debate by considering the energy and angular momentum carried by the magnetic fields expelled from AGB stars. In 2005, Noam Soker claimed that: “*a single star can not supply enough energy and angular momentum to shape those nebulae*”. And later, in 2006, Nordhaus et al. showed that magnetic fields can play an important role in the shaping of bipolar PNe but isolated stars can not sus-

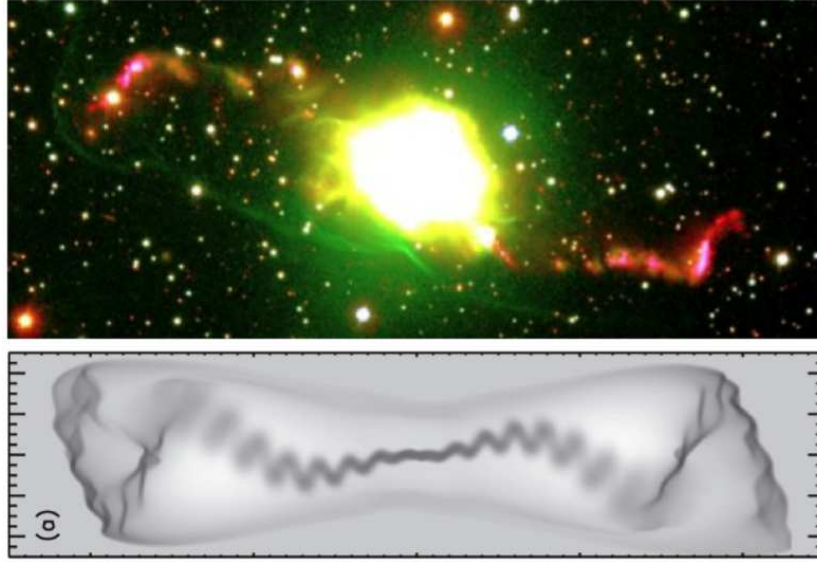


Figure 1. Figure 1: Up: FORS2/VLT colour-composite image of Fleming 1 showing the [O III] envelope around the bipolar jets (from Boffin et al., 2012). The field of view is 5.5×2.3 . The jets show clear indication of precession. Down: three-dimensional gas dynamical simulation from a source in a circular orbit, and with a precessing outflow axis (Raga et al., 2009).

tain a magnetic field for long enough. Magnetic field can thus play a role to collimate jets, but the angular momentum they need to be sustained requires the presence of a binary companion.

4. Direct detection of binaries in PNe

As soon as in 2005, it was quite convincingly shown, from a theoretical point of view, that binary companions should be the main shaping agents of PNe. But, by then, only a handful of binary companions were known. Following an idea by Orsola de Marco, a community effort collaboration started during the Asymmetrical Planetary Nebulae IV conference held in La Palma, aiming at hunting for binaries in the heart of PNe: PLANB¹. Three main methods were used to look for binaries in PNe. The study of flux variability can tell us about eclipses, tidal deformations induced by the companion or irradiation effects. Spectral variability is a measure of radial velocities and enables the discovery of companions as it has been widely shown in the exoplanets community. Finally, central stars of PNe being hot, searching for infrared excess in their core can lead to the detection of cool companions.

The first big leap forward was made thanks to a variability study using OGLE data (Miszalski et al., 2009a). It was then identified that binary stars were discovered in PNe sharing common characteristics (Miszalski et al., 2009b). These characteristics are

¹<http://www.wiyn.org/planb/>

intuitively bipolarity, but also the presence of low ionisation filaments and equatorial rings. Using this, new discoveries were made using both photometric and spectroscopic surveys (e.g. Jones et al. (2010, 2012, 2013); Miszalski (2011a,b,c,2013); Boffin 2012). Spatio-kinematical models (e.g. Jones et al., 2010) were used to lift the degeneracy due to projection effects (a bipolar nebula seen pole-on will appear circular in the sky). These works demonstrate that the orbital plane of the discovered binaries are coincident with the observed equatorial overdensities and perpendicular to the bipolar/multipolar lobes. This is a nice confirmation that binaries play an active role in the shaping of bipolar PNe.

An interesting outcome of these studies is that most of the systems are short period binaries ($P < 3$ days) and certainly went through a common envelope evolution which lead to the shrinking of the orbit (Miszalski et al., 2009). The observed jets appear to be older than the nebulae. It is very likely that the jets were produced during an interaction before a common envelope phase that lead to the formation of the nebula. Fleming 1 (Fig.1) provides a very nice textbook case for this scenario (Boffin et al., 2012). Radial velocities measurements show that its core harbour a binary system with a ~ 1.2 days period. The precessing jets have a timescale of 10^4 years, so that the orbital period while the jets were created should have been $\sim 10^2$ - 10^3 years. But, as measured by radial velocities, the orbital is much shorter. It is thus very likely that the jets formed before a common envelope phase. The orbit shrunk during that phase to become the present close binary system. This lead Boffin et al to claim that: “*Similar binary interactions are therefore likely to explain these kinds of outflows in a large variety of systems*”.

5. Direct detection of binaries in post-AGB stars

As shown before, more and more binary systems are being discovered in PNe. The detection of binaries in post-AGB systems is made more complex by the fact that the central stars are pulsating and embedded in dust. This makes the three techniques used for hunting binaries in PNe (radial velocities, photometric variation and infrared excess) difficult to apply. Morphological studies using high angular resolution infrared images show that spherical proto-PNe (post-AGB stars on their way to form PNe) are very rare (Lagadec et al., 2011). O-rich PPNe are predominantly bipolar or multipolar. Their low C/O could be due either to the interaction with a binary companion during a common envelope phase or hot bottom burning converting carbon to nitrogen (De Marco, 2009). The common envelope scenario will lead to an ejection of the envelope earlier than during single star evolution, leading to a lower C/O ratio, as less carbon is dredged-up to the surface (Izzard et al. 2006). Hot bottom burning occurs in the most massive AGB stars, making it likely that the bipolar PPNe have progenitor with larger masses than the elliptical ones in agreement with the work by Corradi & Schwartz (1995). This could be explained in the frame of the binary system progenitors paradigm as primaries that undergo a common envelope phase, and thus become bipolar, tend to have a higher mass (Soker, 1998).

Binaries have however been discovered in two emblematic bipolar post-AGBs. From the position of the different masers in OH 231.8+4.2, Gomez et al. (2001) found that it was a binary system, but the central star of OH 231.8, QX Pup is actually a Mira star. A binary system was also discovered in the iconic post-AGB star the Red Rectangle (Waelkens et al., 1996), with a period of 318 days. This orbit is too small

to host an AGB star, so that the object must have evolved from a binary channel. It is widely agreed that the bipolar morphology of this object is due to the interaction with a binary companion.

A very interesting systematic search for binaries in post-AGBs has been performed by Bruce Hrivnak and his undergraduate students at Valparaiso University. They have been doing radial velocities monitoring of post-AGB stars till 1994, hunting for long period binaries. They might have detected a binary system with $P > 22$ years (Hrivnak et al., 2011). Their result tend to indicate that potential binary companions have e periods greater than 25 yr or masses of brown dwarfs or super-Jupiters.

Another large scale hunt for binaries in post-AGB was initiated by Hans van Winckel and collaborators. Their targets were selected based on the presence of a near-infrared excess in their spectral energy distribution (de Ruyter et al., 2006). This excess is due to the presence of dust near the sublimation temperature, in a stable, compact ($R \sim 10$ AU), Keplerian disc, as confirmed by their infrared interferometric measurements (Deroo et al., 2007). Radial velocities monitoring indicates that close binary systems (0.5-3 AU) are present in the core of those discs (van Winckel et al., 2009). They also found that all the discs were oxygen-rich and no photospheric evidence for dredge-up. The binary companion thus has an influence on the chemical evolution of the star and can prevent dredge up from forming carbon-rich objects. Such discs are very likely to be formed in all the binary systems too small to accommodate a fully grown up AGB star. Compact, Keplerian discs in post-AGB stars are thus very likely indirect evidence for binary interaction. To quote Olivier Chesneau: *"My personal opinion is that the discovery of a stratified disk with proved Keplerian kinematics is directly connected to the influence of a companion, albeit the few exceptions presented above, namely the Young Stellar Objects or the critical velocity rotating massive sources such as Be stars. This hypothesis must be confirmed by further observations"*.

6. Detection of binaries in AGB stars

The direct detection of a companion by the aforementioned techniques in an AGB star is made very difficult by the large scale pulsation of AGB star and their infrared brightness due to the dust in their envelopes.

High angular resolution observations of their envelopes have revealed that many AGB stars are actually asymmetrical. The iconic carbon-rich AGB star is known to display a more or less spherically symmetric envelope at large scale, as seen through dust scattered ambient Galactic light (Mauron & Huggins, 1999; Leao et al., 2006). However, when one peers deep into its core using infrared high angular resolution observations, such as speckle imaging (Weigelt et al., 1998) or adaptive optics (Leao et al., 2006), one can clearly detect the presence of clumps. CO observation of V Hya also revealed the presence of a fast, bipolar outflow and an equatorial disc (Hirano et al., 2004, Sahai et al., 2003). A disc was also detected around one of the closest AGB stars, (L₂ Pup) using near-infrared adaptive optics imaging (Kervella et al., 2014). The morphologies of these objects seems to indicate that they are the progenitors of bipolar PNe. If one accepts the proposed idea that bipolar PNe are due to binary interaction, their progenitors should be binary systems. The AGB stars we mentioned before are thus very likely binary systems.

It is very difficult to directly detect those binaries, but indirect techniques can be used. Using hydrodynamics simulation of dusty winds in binary systems, Mastrode-

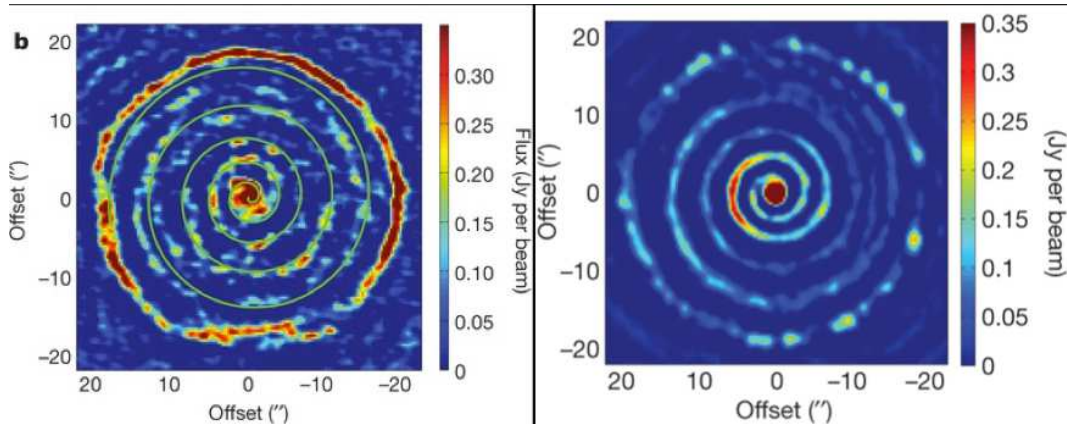


Figure 2. Figure 2: Left: ALMA CO 3-2 map of the AGB star R Scl, revealing the presence of a detached shell and a spiral pattern. Right: SPH model of an interacting binary system containing an AGB transferring material to his companion via Wind Roche-Lobe overflow to form the observed spiral pattern.

mos & Morris (1999) have shown that shocks between the wind of an AGB star and a companion star can lead to the formation of a dusty spiral covering most of the solid angle around the binary. Mohamed and Podsiadlowski (2007) found that a similar spiral could be the outcome of the interaction an AGB wind with a binary with simulation of a new mass-transfer mode: wind Roche-lobe overflow. When the wind acceleration occurs at a few stellar radii, close to the Roche-lobe, as in Mira stars, the wind can fill the Roche lobe. Material can then be transferred, like in traditional Roche-lobe overflow. One of the most striking results obtained with ALMA so far is the direct detection of such a spiral pattern around the AGB star R Scl (Fig.2, Maercker et al., 2012). Detecting spiral around AGB star is thus an indirect evidence for a binary companion. Those spirals are Archimedes spiral with a constant spacing. Knowing the pitch of the spiral and the expansion velocity of the wind (which can be measured with ALMA), one can easily determine the period of the binary system. Such spiral patterns have been detected around other AGB stars in reflected light for AFGL 3068 (Mauron & Huggins (2006) and CIT 6 (Kim et al., 2013) and with ALMA CO observation in Mira (Ramstedt et al., 2014) and for IRC +10216 (Homan, these proceedings) . One way to find a large number of interacting binaries in AGB stars would be to perform surveys looking for such spiral patterns. Such surveys could be done either with large scale optical imagers, looking for dust reflection by ambient Galactic light, high angular resolution adaptive imaging (probably with coronagraphy to reach high contrasts and why not directly detect the companion) or direct CO imaging with millimetre interferometers such as ALMA. The two first techniques probe the dust, while CO observations probe the gas and also measure the shell expansion velocities, leading to an accurate determination of the binary separation. Another interesting approach is to perform a multi-scale/multi-wavelengths approach and study the circumstellar material from the dust formation radius till its interaction with the interstellar medium (see Mayer and Paladini, these proceedings).

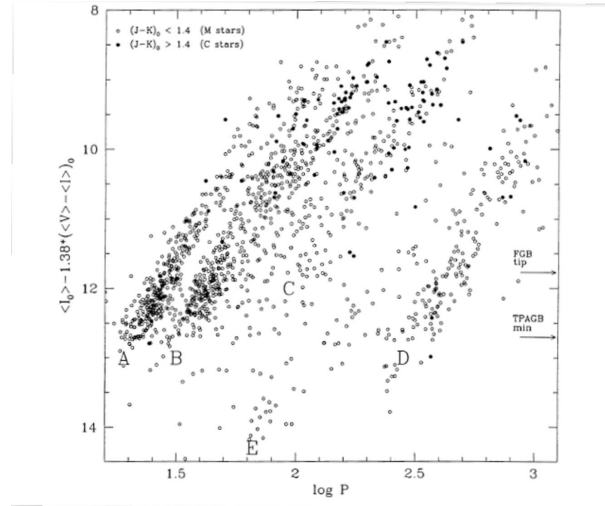


Figure 3. Figure 3: Period luminosity diagram for red giants in the Large Magellanic Cloud ($\langle I \rangle$ and $\langle V \rangle$ are mean magnitudes and P in days. Star on sequence A to D are giant stars pulsating in the fundamental modes and different overtones. The stars on sequence E have a light variability due to the presence of a binary companion. (Figure from Wood (1999))

Another technique to indirectly discover binaries in AGB star is looking for ultra-violet excess. AGB stars being cool, they are very faint in the UV. Sahai et al. (2008) performed a small UV imaging survey using GALEX). They observed 25 AGB stars and found a UV excess in 9 of them. This UV excess likely result either from the presence of a hot companion, or from accretion induced by a companion.

Finally, binaries in AGB stars can be found using observations in nearby galaxies. As we know the distance to those galaxies, luminosities can be accurately determined, unlike in the Milky Way. Determining period for the AGB variables enable the obtention of period luminosity diagrams (Fig. 3; see e.g. Wood et al., 1999 for the Large Magellanic Cloud (LMC)). Five distinct period-luminosity sequences have been found on the low mass giant branch. Star on sequence A to D are giant stars pulsating in the fundamental modes and different overtones. The stars on sequence E have a light variability due to the presence of a binary companion (see e.g. Nicholls et al., 2010). Those stars are likely the precursors of PNe with close binary central stars and binary post-AGB and post-RGB stars.

These stars are likely the immediate precursors of planetary nebulae (PNe) with close binary central stars as well as other binary post-asymptotic giant branch (post-AGB) and binary post-red giant branch (post-RGB) stars. Binary post-RGB stars are similar to binary post-AGB stars, but the interaction with the companion lead to the formation of a disc as soon as the RGB phase. It is almost impossible to distinguish post-RGBs from post-AGBs in the Galaxy as the main difference between the two classes of objects is their luminosities. Post-RGB stars can be more easily discovered in nearby galaxies with known distances, where there luminosity can be easily determined (see e.g. Kamath et al., 2014). A population study of binary AGBs, post-RGBs and post-AGBs in the LMC show that between 3 and 19 % of the PNe come from single stars

while $\sim 50\%$ of the PNe with close binary precursors have post-RGB precursors (Nie et al., 2012). The interaction with a binary companion can thus prevent a low or intermediate mass star from becoming an AGB star.

7. Conclusions and perspectives

In this review, we have shown that binarity was common in AGB, post-AGB (post-RGB) stars and PNe. If the binary companion is close/large enough, it can lead to the formation of a common envelope or a disc. The presence of a binary can affect the chemical evolution of a star by quickly ejecting its circumstellar envelope. This can prevent stars from becoming carbon-rich, as the envelope is ejected before dredge-up brings enough carbon to the surface to make it carbon-rich. If the companion is close enough, this can even prevent the star from becoming an AGB star and form a post-RGB star. In case of mass transfer, the secondary can be enriched in s-processed elements and lead to the formation of peculiar objects such as the Barium stars, the carbon-enhanced metal poor stars or the CH stars (see the nice review by Jorissen, 1999).

To better understand the impact of binarity on the evolution of low and intermediate mass stars, we need to better understand how binaries form discs and how these discs evolve. These discs will have an impact on the chemical composition of the stars, as dust will form and refractory elements will deplete on dust. These discs could also impact the evolution timescales of the central stars and change their mass-loss history and thus their chemical enrichment.

Finally, to better understand how binarity affects the evolution of a star during the AGB, we should start a large scale survey of AGB stars with binary companion, to characterise its population (binary fraction, mass ratio and separation of the components) and study how these parameters affect the chemical evolution of the AGB stars. This will enable to quantify the impact of binarity on the chemical evolution of galaxies and maybe start a new series of conferences: *Why do galaxies care about binary AGB stars?*

Acknowledgments. This review is dedicated to the memory of Olivier Chesneau, who left us too early. Olivier was a bright and passionate astronomer who inspired many young researchers and opened new horizons to the evolved star community. E.L. would like to thanks David Jones, Henri Boffin, Hans van Winckel and Albert Zijlstra for fruitful discussions during the preparation of this review.

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